

**AN APPARATUS FOR MOVING A PAIR OF OPPOSING SURFACES IN
RESPONSE TO AN ELECTRICAL ACTIVATION**

FIELD OF THE INVENTION

[0001] The present invention relates to an apparatus for moving a pair of opposing surfaces in response to an electrical activation.

BACKGROUND OF THE INVENTION

[0002] Various types of piezoelectric devices are known to those skilled in the art. Many of these devices include complex configurations and are very expensive to manufacture. Other devices include simpler configurations, but are extremely limited in the corresponding maximum range of movement or the corresponding maximum application of force.

[0003] In such known devices, when the piezoelectric actuator is electrically activated, the rectangular prism geometry of the device expands predominantly along a predetermined axis. When the piezoelectric device is deactivated, the geometry of the device contracts predominantly along the predetermined axis. This expansion and contraction of the piezoelectric device can be used to operate an apparatus, e.g. to open and close a clamp or valve. An apparatus for clamping or valving typically includes a support having two members spaced with respect to each other. The piezoelectric device is transversely disposed between the two spaced members. As the piezoelectric device expands in a linear direction, the members are driven or pivoted along a curvilinear path. The pivoting of the members along a curvilinear path results in an inefficient transfer of force from the piezoelectric device to the support. The piezoelectric actuator in most known configurations is positioned parallel to the desired motion providing little opportunity to select different hinge axis locations and/or structural configurations to optimize performance.

SUMMARY OF THE INVENTION

[0004] The present invention provides an apparatus for moving a pair of opposing surfaces in response to an electrical activation. The apparatus includes a support including a rigid non-flexing portion, first and second pivotable arm portions

extending from the rigid portion, a pair of opposing surfaces with one opposing surface on each pivotable arm portion for movement relative to one another, and a force transfer member operably positioned between the first and second pivotable arm portions. An actuator is operably engaged between the rigid non-flexing portion and the force transfer member to drive the force transfer member in movement along a fixed path causing at least one of the first and second pivotable arm portions to pivot in response to an electrical activation of the actuator. The support and force transfer elements of the structure are designed to be rigid, non-flexing elements. Any unplanned flexing can reduce the effective life of the mechanism, and reduces the amount of force transferred through the hinge axes to pivot the arms. The reduction in force limits the displacement and force of the pivoting arms. The selection of the hinge axis location and corresponding structural configuration allows substantial capability to optimize the performance of the apparatus for the particular application.

- [0005] The piezoelectric actuator can be preloaded with force when installed in the support element. For example, the piezoelectric actuator can be clamped within the support structure with an adjustable screw supporting one end allowing optimal force preloading. An adjustable screw configuration is easy to use and allows a large degree of adjustability. Preloading the piezoelectric actuator in any suitable fashion contributes to maximum efficiency of force transfer during actuation, and allows fine tuning of the initial position of the of the apparatus prior to actuation of the piezoelectric element. Preloading can also ensure that the piezoelectric actuator maintains contact with the apparatus at opposite ends throughout the range of expansion and contraction. The use of a threaded adjustment screw for preloading enables assembly without requiring adhesives or other means of securely connecting the piezoelectric actuator at opposite ends to the apparatus, and avoids the possibility of damaging tension or torsional moments on the piezoelectric actuator. The threaded adjustment screw allows simple compensation for dimensional variations in the piezoelectric actuator during assembly to the support.

- [0006] Other applications of the present invention will become apparent to those skilled in the art when the following description of the best mode contemplated for practicing the invention is read in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

- [0007] The description herein makes reference to the accompanying drawings wherein like reference numerals refer to like parts throughout the several views, and wherein:
- [0008] Figure 1 is a perspective view of one embodiment of an apparatus for moving a pair of opposing surfaces in response to an electrical activation having a support and an actuator in accordance with the present invention;
- [0009] Figure 2 is a side view of the apparatus of Figure 1 with the actuator deactivated;
- [0010] Figure 3 is an exaggerated side view of the apparatus of Figure 1 with the actuator partially activated;
- [0011] Figure 4 is an extremely exaggerated side view of the apparatus of Figure 1 with the actuator fully activated;
- [0012] Figure 5 is a second embodiment of the apparatus with the support including a force transferring member having an alternative shape;
- [0013] Figure 6 is a third embodiment of the apparatus with the support including an adjustable seat;
- [0014] Figure 7 is a simplified flow chart illustrating the process of optimizing the flex axis of the present invention; and
- [0015] Figure 8 is a set of separate intersecting curves showing force versus displacement for the mechanical support and the piezoelectric element according to a process of the present invention for optimizing the hinge geometry of the mechanical support.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

- [0016] Figure 1 is a perspective view of one embodiment of an apparatus 10 having a support 12 and an actuator 14 in accordance with the present invention. The support 12 includes a rigid, non-flexible portion 16, at least one pivotable arm portion, such as first and second pivotable arm portions 18 and 20 extending from the rigid portion 16, a pair of opposing surfaces 22 and 24 with one opposing surface 22, 24 on each pivotable arm portion 18, 20 for movement relative to one another, and a force transfer member 26 operably positioned between the first and second pivotable

arm portions 18 and 20. Preferably, the support 12 is a unitary, integral, single-piece body. The actuator 14 is operably engaged between the rigid, non-flexible portion 16 and the force transfer member 26 to drive the force transfer member 26 linearly causing the first and second pivotable arm portions 18, 20 to pivot about corresponding axes and drive the opposing surfaces 22 and 24 apart or away from each other in response to an electrical activation from a controller 28 in communication with the actuator 14.

[0017] When activated, the actuator 14 is designed to produce a positional or spatial displacement predominately along one predetermined axis. The function of the actuator 14 can be performed by one of several different types of piezoelectric devices including an individual piezoelectric element, a stack of individual piezoelectric elements, a mechanically amplified piezoelectric element or stack, or, preferably, a multilayer cofired piezoelectric stack.

[0018] When a voltage is applied across the piezoelectric device, the device receives and stores an electrical charge. When charged, the piezoelectric device expands predominately along the one predetermined axis. The expansion of the piezoelectric device produces a spatial displacement along the one predetermined axis increasing the initial uncharged thickness of the device. In this manner, the one predetermined axis functions as an axis of displacement. The amount of electrical charge stored by the piezoelectric device is generally proportional to the amount of voltage applied across the device up to a maximum voltage limit. The amount of expansion along the one predetermined axis is generally proportional to the amount of electrical charge stored by the piezoelectric device. Thus, the amount of expansion along the one predetermined axis can be controlled by varying the amount of voltage applied across the piezoelectric device. For example, applying the maximum amount of voltage across the piezoelectric device produces a maximum amount of expansion along the one predetermined axis and applying one-half the maximum amount of voltage across the piezoelectric device produces approximately one-half the maximum amount of expansion along the one predetermined axis.

[0019] The electrical charge on the piezoelectric device is discharged or dissipated when the device is (1) connected directly to ground, (2) electrically shorted

directly across the terminal ends, or (3) electrically shorted or grounded through an impedance. When discharged, the piezoelectric device contracts or shrinks along the one predetermined axis back toward the initial uncharged thickness of the device. The discharge of the piezoelectric device can be controlled to produce a spatial displacement along the one predetermined axis decreasing the thickness of the device.

[0020] The controller 28 is designed to operate the apparatus 10. To produce a spatial displacement along the predetermined axis, the controller 28 provides a charging voltage across the piezoelectric device. Typically, the amount of spatial displacement is approximately proportional to the charging energy. To return the piezoelectric device to the initial uncharged thickness, the controller 28 provides the necessary discharge means (i.e. the controlled electrical grounding or shorting) described above. The controller 28 is designed to completely charge and completely discharge the piezoelectric device. As a result, the opposing surfaces 22 and 24 of the apparatus 10 are maintained in either a fully open or fully closed position. The controller 28 can be designed to partially charge and partially discharge the piezoelectric device, if desired. As a result, the opposing surfaces 22 and 24 of the apparatus 10 can be maintained in the fully open position, the fully closed position, or any position therebetween (i.e any partially open or partially closed position). The partial opening and closing of the opposing surfaces 22 and 24 can be based directly on sensor feedback or on an algorithm processing such sensor feedback. The controller 28 can be further designed to recycle discharged power by storing power discharged from the piezoelectric device and reusing such power during the next charging of the piezoelectric device. The controller 28 can also be designed to supply such recycled discharged power to one or more other piezoelectric or non-piezoelectric devices.

[0021] Figure 2 is a side view of the first embodiment of the apparatus 10. Preferably, the rigid, non-flexing portion 16 of the apparatus 10 is C-shaped including a rigid non-flexing web 30 extending between a pair of rigid non-flexing arm portions 32, 34. At least one pivotable arm portion 18 is pivotably connected via a living integral hinge 36 to one rigid arm portion 32. Another pivotable arm portion 20 can

optionally be pivotably connected via a living integral hinge 38 to the other rigid arm portion 34, if two opposing pivotable arms are desired. The force transfer member 26 includes a seat surface 40.

[0022] The actuator 14 includes opposite ends 42 and 44 and, as described above, the actuator 14 produces a controlled spatial displacement between the opposite ends 42 and 44 in response to an electrical activation. One end 42 of the actuator 14, hereinafter referred to as the set or fixed end 42, is disposed adjacent to the rigid web 30. The other end 44 of the actuator 14, referred to hereinafter as the driving end 44, is disposed adjacent to the seat surface 40 of the force transfer member. Thus, the actuator 14 is operably engaged between the nonflexing web 30 and the force transfer member 26 for driving the force transfer member 26 away or apart from the rigid web 30 in response to an electrical activation of the actuator 14. In other words, the piezoelectric device is oriented such that the axis of greatest displacement is aligned perpendicular to the web 30 and the seat surface 40.

[0023] In Figure 2, the actuator 14 is deactivated. The opposing surfaces 22 and 24 are closest to each other when the actuator 14 is deactivated. This type of configuration is commonly referred to as a normally closed design. When the actuator 14 is electrically activated, the set end 42 of the actuator 14 is held fixed by the rigid portion 16, the driving end 44 of the actuator 14 drives the force transfer member 26 away or apart from the rigid web 30 (i.e. to the right in Figure 2), and the first and second pivotable arm portions 18 and 20 are pivoted about living integral hinges 36 and 38 respectively. In this manner, the space or distance between the opposing surfaces 22 and 24 is increased. In other words, when a voltage is applied across the piezoelectric device, the spatial displacement produced along the predetermined axis drives the force transfer member 26 away or apart from the rigid portion 16 pivoting the first and second pivotable arm portions 18 and 20 about the living integral hinges 36 and 38 respectively thus increasing the space or distance between the opposing surfaces 22 and 24. The opening of the opposing surfaces 22 and 24 can be adjusted by varying the amount of voltage applied across the piezoelectric device.

[0024] The support 12 is composed of a material having shape memory. Typically, the support material has a high modulus of elasticity and high strength. As

a result, the apparatus 10 can be made from a variety of materials including, but not limited to, a metal, such as steel or other metals, an alloy, such as Inconel or other alloys, or a composite material, such as ThorneL.

[0025] When the actuator 14 is deactivated, the opposing surfaces 22 and 24 are biased toward one another by the shape memory of the support structure material provided the support 12 has not been plastically deformed. In other words, when the piezoelectric device is discharged, the piezoelectric device shrinks or contracts along the axis of expansion and the shape memory of the support structure material biases the force transfer member 26, the first and second pivotable arm portions 18 and 20, and the opposing surfaces 22 and 24 back toward the original shape of the apparatus 10. The closing of the opposing surfaces 22 and 24 can be adjusted by controlling the discharge of the piezoelectric device.

[0026] The present invention maximizes the transfer of force from the expansion of the actuator 14 through the force transfer member 26 to the pivoting of the pair of pivotable arm portions 18 and 20 and the opening of the opposing surfaces 22 and 24. For maximum force transfer, the set end 42 of the actuator 14 is fixed by the rigid portion 16. In other words, the apparatus 10 is designed so the rigid portion 16 does not flex or bow when the actuator 14 is activated. In this manner, all of the actuator expansion force is directed through the driving end 44 of the actuator 14 toward the force transfer member 26. To transfer the maximum force from the actuator 14 to the pair of pivotable arm portions 18 and 20, the force transfer member 26 is designed so that the seat surface 40 does not flex or bow when the actuator is activated. The driving end 44 of the actuator 14 remains in operable contact or optimal force transferring contact with the seat surface 40 of the force transfer member 26 at all spatial displacements of the actuator 14, i.e. at the minimum operating spatial displacement, the maximum operating spatial displacement, and all spatial displacements of the actuator therebetween. In other words, the driving end 44 of the actuator 14 remains in operable contact or optimal force transferring contact with the seat surface 40 of the force transfer member 26 when the actuator is deactivated, partially activated, and fully activated.

[0027] In the first embodiment of the apparatus 10, the driving end 44 of the actuator 14 has a planar surface and the seat surface 40 of the force transfer member 26 is a planar surface with the planar end surface 44 of the actuator 14 disposed adjacent to the planar seat surface 40 of the force transfer member 26. Figure 2 illustrates the planar driving end 44 of the actuator 14 in operable contact with the planar seat surface 40 of the force transfer member 26 when the actuator is deactivated. Figure 3 illustrates the planar driving end 44 of the actuator 14 in operable contact with the planar seat surface 40 of the force transfer member 26 when the actuator 14 is partially activated and is exaggerated to show a larger opening between the opposing surfaces 22,24 than would normally be seen. Figure 4 is also exaggerated to illustrate the planar driving end 44 of the actuator 14 in operable contact with the planar seat surface 40 of the force transfer member 26 when the actuator 14 is fully activated and shows a larger opening between the opposing surfaces 22,24 than would actually be seen in the fully activated position.

[0028] Figure 5 is a second embodiment of the apparatus 10a with the force transfer member 26a having an alternative T-shape. The apparatus 10a includes a support 12a and an actuator 14a similar to that previously described for the other embodiments. The support 12a includes a rigid non-flexing portion 16a, at least one pivotable arm portion 18a, 20a extending from the rigid non-flexing portion 16a, a pair of opposing surfaces 22a, 24a with one opposing surface 22a, 24a on each pivotable arm portion 18a, 20a for movement relative to one another, and a force transfer member 26a operably positioned between the first and second pivotable arm portions 18a, 20a. Preferably, as with the other embodiments the entire support 12a is formed as a unitary, integral, single-piece body. The actuator 14a is operably engaged between the rigid portion 16a and the force transfer member 26a to drive the force transfer member 26a in linear motion away from the rigid web 30. Movement of the force transfer member 26a pivots the first and second pivotable arm portions 18a, 20a about the living integral hinges 36a, 38a respectively. A controller (not shown) can be provided to operate the apparatus 10a. The controller can provide a charging voltage across a piezoelectric device to produce spatial displacement along a predetermined axis as previously described for the other embodiments. The rigid portion 16a of the

apparatus 10a can include a C-shaped web 30a extending between a pair of rigid arm portions 32a, 34a. One pivotable arm portion 18a is pivotably connected via the living integral hinge 36a to one rigid non-flexing arm portion 32a, and the other pivotable arm portion 20a is pivotable connected via the living integral hinge 38a to the other rigid non-flexing arm portion 34a. The force transfer member 26a can include a seat surface 40a. The actuator 14a includes opposite ends 42a and 44a. The actuator 14a produces a controlled spatial displacement along the predetermined axis between opposite ends 42a and 44a in response to an electrical activation. One end 42a of the actuator 14a, such as a set or fixed end 42a, is disposed adjacent to the rigid web 30a. The other end 44a of the actuator 14a, such as a driving end 44a, is disposed adjacent to the seat surface 40a of the force transfer member 26a. When the actuator 14a is electrically activated, the set end 42a of the actuator 14a is held fixed by the rigid portion 16a, the driving end 44a of the actuator 14a drives the force transfer member 26a away or apart from the rigid portion 16a (i.e. to the right in Fig. 5), and the first and second pivotable arm portions 18a, 20a are pivoted about the living integral hinges 36a, 38a respectively. In this configuration, the forces transferred from the force transfer member 26a to the pivotable arm portions 18a, 20a are transmitted through force transfer webs or hinges 48a, 50a extending between the force transfer member 26a and the corresponding pivotable arm portions 18a, 20a. The line of force transfer is generally parallel to the predetermined axis of spatial expansion of the piezoelectric actuator 14a, and preferably perpendicular to the fulcrum axis or axis of rotation of the pivotable arm portions 18a, 20a about the corresponding living integral hinges 36a, 38a.

- [0029] Figure 6 is a third embodiment of the apparatus 10b with an adjustable seat 52b supported by the rigid portion 16b with an adjustable support 54b. The apparatus 10b includes a support 12b and an actuator 14b similar to that previously described for the other embodiments. The support 12b includes a rigid non-flexing portion 16b, at least one pivotable arm portion 18b, 20b extending from the rigid non-flexing portion 16b, a pair of opposing surfaces 22b, 24b with one opposing surface 22b, 24b on each pivotable arm portion 18b, 20b for movement relative to one another, and a force transfer member 26b operably positioned between the first and

second pivotable arm portions 18b, 20b. Preferably, as with the other embodiments the entire support 12b is formed as a unitary, integral, single-piece body. The actuator 14b is operably engaged between the rigid portion 16b and the force transfer member 26b to drive the force transfer member 26b in linear motion away from the rigid portion 16b. The rigid portion 16b supports with an adjustable support 54b an adjustable seat 52b having a complementary surface to the end 42b of the actuator 14b. The complementary surface of the adjustable seat 52b can be flat or shaped in any manner to support the actuator 14b in a position suitable for driving the force transfer member 26b in response to electrical actuation of the actuator 14b.

Movement of the force transfer member 26b pivots the first and second pivotable arm portions 18b, 20b about the living integral hinges 36b, 38b respectively. A controller (not shown) can be provided to operate the apparatus 10b. The controller can provide a charging voltage across a piezoelectric device to produce spatial displacement along a predetermined axis as previously described for the other embodiments. The rigid portion 16b of the apparatus 10b can include a web 30b extending between a pair of rigid arm portions 32b, 34b. One pivotable arm portion 18b is pivotably connected via the living integral hinge 36b to one rigid arm portion 32b, and the other pivotable arm portion 20b is pivotably connected via the living integral hinge 38b to the other rigid arm portion 34b. The force transfer member 26b can include a seat surface 40b. The actuator 14b includes opposite ends 42b and 44b. The actuator 14b produces a controlled spatial displacement along the predetermined axis between opposite ends 42b and 44b in response to an electrical activation. One end 42b of the actuator 14b, such as a set or fixed end 42b, is disposed adjacent to the rigid web 30b as shown in the previous embodiments, or supported by the adjustable seat 52b connected to the rigid web 30b. The other end 44b of the actuator 14b, such as a driving end 44b, is disposed adjacent to the seat surface 40b of the force transfer member 26b. When the actuator 14b is electrically activated, the set end 42b of the actuator 14b is held fixed by the adjustable seat 52b connected to the rigid portion 16b, the driving end 44b of the actuator 14b drives the force transfer member 26b away or apart from the rigid portion 16b (i.e. to the right in Fig. 6), and the first and second pivotable arm portions 18b, 20b are pivoted about the living integral hinges

36b, 38b respectively. In this configuration, the forces transferred from the force transfer member 26b to the pivotable arm portions 18b, 20b are transmitted through force transfer webs or hinges 48b, 50b extending between the force transfer member 26b and the corresponding pivotable arm portions 18b, 20b. The line of force transfer is generally parallel to the predetermined axis of spatial expansion of the piezoelectric actuator 14b, and preferably perpendicular to the fulcrum axis or axis of rotation of the pivotable arm portions 18b, 20b about the corresponding living integral hinges 36b, 38b. It should be recognized that the adjustable support 54b and complementary seat 52b illustrated in Figure 6 can be used in the other embodiments illustrated in Figures 1-5 without departing from the spirit and scope of the present invention.

[0030] Referring now to the invention in general, the apparatus according to the present invention is based on mechanical conversion of the motion and force of the actuator by means of the force transfer member. The actuator is preferably a solid state device that increases its size in one or more dimensions when electrically or magnetically stimulated. An example of such a device is a cofired piezoelectric stack. Further, the device preferably has a rectangular prism geometry. The actuator is disposed within the body cavity of the support. The body cavity is bounded on one side by the inside surface of the rigid non-flexing web and on the other side by the inside surface of the moveable force transfer member. The body cavity is further bounded by the upper inside surface of the support defined by the rigid non-flexing arm portion and the opposing lower inside surface of the support defined by the rigid non-flexing arm portion. The actuator is mounted within the body cavity so that one face or end of the actuator is in direct contact with the inside surface of the web, while the opposing face or end of the actuator is in direct contact with the inside surface of the force transfer element. In other words, the actuator is under continuous compression from the inside surface of the web and the inside surface of the force transfer element. If desired, an adjustable rigid non-flexing support member can be connected to the web for adjustably supporting the one face of the actuator in compression against the opposing face of the force transfer element.

[0031] The actuator is actuated by application of appropriate electrical power.

The electrical power is controlled by a controller similar to that illustrated as 28 in Figure 1. The controller, in its simplest form, can be a switching device. The controller is connected to the actuator via electrical wires. The controller can have multiple embodiments. For example, it can be designed to fully actuate and fully deactivate the actuator. It can be designed to actuate the actuator to any increment between fully extended and fully retracted. It can also be designed to reuse or redirect the power in the actuator to optimize efficiency.

[0032] When the actuator is deenergized or unactuated, it is at a rest position with initial uncharged dimensional conditions. When energized or actuated, the actuator expands along one or more axes as determined by the material properties of the actuator. This expansion is due to the piezoelectric, electrostrictive, or magnetoresistive phenomenon depending on the type of actuator actually used in a specific embodiment of this invention. The actuator is designed so that the spatial dimension of maximum expansion when actuated is in line with the two bounding inside surfaces of the web and the force transfer member. Since the actuator is under compression by the two bounding inside surfaces of the web and force transfer member, when the actuator is electrically actuated and expands along the primary expansion axis, the actuator will exert additional pressure against the two bounding inside surfaces.

[0033] The web is designed to provide a rigid structure for the actuator to push directly against, or indirectly against through the adjustable seat. Since the web constrains the actuator, the force transfer element, which is designed to move within the apparatus, is displaced by the expanding actuator. The force transfer element in turn is connected via integral hinges or webs, to the upper pivotable arm and the lower pivotable arm. The force transfer element is connected to the upper and lower arms with webs, and the integral hinges divide the pivotal arm portions from the rigid arm portions of the support. Both rigid non-flexing arm portions serve as structural members integral with the rigid non-flexing web. The hinges are designed so that the force and displacement generated by the piezoelectric element travel through the force transfer element and are focused and applied extremely close to the fulcrum of the

hinges. Therefore, the force transfer element transfers a substantial portion of the force and displacement of the expanding actuator to the pivotable arms through the webs. The apparatus is designed so that the expansion of the actuator causes the upper and lower pivotable arm portions to pivot outward about the integral hinges so that the face of one of the pivotable arm separates from the face of the other pivotable arm. Deactuation of the actuator restores the spatial displacement of the force transfer element to the initial position along the predetermined axis. This in turn causes the overall structure of the support to revert to the initial or rest state.

[0034] The piezoelectric actuator is preferably preloaded with force when installed in the support. If desired, the piezoelectric actuator can be clamped within the support with an adjustable seat positioned between the rigid non-flexing web and one end of the actuator. By way of example and not limitation, an adjustable screw configuration can be used for this purpose, or any other suitable arrangement allowing for optimal force preloading on the piezoelectric actuator can be provided. Preloading contributes to maximum efficiency of force transfer from the piezoelectric actuator to the support during actuation. Preloading also allows fine tuning of the initial, uncharged position of the apparatus according to the present invention. Proper preloading ensures that the piezoelectric actuator remains in contact with the support at both ends during the full range of expansion and contraction without requiring the use of adhesive or other measures to secure the piezoelectric actuator to the support. Preloading also helps to avoid the possibility of subjecting the piezoelectric actuator to undesirable tension or torsional moments, which could cause damage. An adjustable seat for one end of the piezoelectric actuator allows for simple compensation of dimensional variations of the piezoelectric actuator during assembly of the apparatus.

[0035] The present invention is disclosed and discussed in detail with respect to at least one pivotal arm portion, and preferably two opposing pivotal arm portions. It should be recognized that the present invention includes both symmetrical and asymmetrical movement of the pivotal arm portions. If desirable, the integral hinges can be provided to provide non-symmetric operation of at least one pivotal arm portion. By way of example and not limitation, this type of movement can be desirable in some valving or clamping configurations.

[0036] Referring now to Figure 7, a simplified flow chart illustrates the optimization of the orientation of the hinge members of the mechanical support according to the present invention. Beginning at step 100, the requirements of the application are defined. The requirements can be a selection of parameters, by way of example and not limitation, including the parameters of force, displacement, size, operating frequency, cycle life, temperature, operating voltage, operating power, vibration, impact resistance, environmental resistance, corrosion resistance, production cost, hysteresis, linearity, and/or repeatability. After the requirements are defined in step 100, the process continues to step 102 where specifications and preliminary geometry of the mechanical support are developed. The process then continues to step 104 where two dimensional (2D) static stress analysis is performed to optimize the hinge geometry of the mechanical support. A three dimensional (3D) computer aided design (CAD) model is then designed in step 106 based on the optimized geometry obtained in step 104. Finite element stress analysis (FEA) is then conducted in step 108 to predict performance of the mechanical support and piezoelectric element. In conducting the analysis, it has been found useful to apply 20% of the maximum force of the piezoelectric element to the force arms for one series of analysis. It has also been found useful to run a series of analysis while constraining the arms of the mechanical support and applying force to the force transfer element to determine the force available from the pivotable arms with no displacement. As a result of the finite element stress analysis separate curves are developed of force versus displacement for the mechanical support and the piezoelectric element. These curves are graphed on the same common axes in step 110 to determine if an intersection of the curves occurs. By way of example and not limitation, one set of these curves is illustrated in Figure 8, where the piezoelement curve is labeled 122 and the mechanical support curve is labeled 124. Figure 8 illustrates an exemplary intersection of the two curves 122,124 at the point labeled 126. The identification of the intersection of the curves occurs in step 112. In query 114, it is determined if the intersection satisfies the force and displacement requirements previously set in step 100. If the requirements are not satisfied, the process branches back to step 102, where the model can be modified and reanalyzed.

If the requirements are satisfied, the process branches to step 116. In step 116, the finite element stress analysis is performed again using the values corresponding to the point 126 of intersection of the two curves 122, 124. The process then proceeds to query 118 to determine if the performance is verified against the application requirements selected in step 100. If the performance is not verified, the process branches back to step 102, where the model can be modified, and reanalyzed. If the performance is verified, the process ends at step 120.

[0037] The apparatus is designed using finite element analysis to meet several criteria. The support must provide repeated operation. Operating life in excess of 100 million cycles can reasonably be expected. For a given actuator, the length of the pivotable arm portions, and the geometry of the integral hinges can be designed to provide varying amounts of separation of the faces.

[0038] A characteristic of this invention is that the force transfer element, the hinges, the pivotable arm portions, the rigid arm portions, and the web are an integral, single, unitary, or monolithic body. That is, there are no fasteners joining these components. Elimination of the fastening methods results in highly efficient transfer of force and displacement from the actuator to the support.

[0039] Another characteristic of the support of the present invention is that the actuator is oriented so that the primary axis of expansion is at a right angle with respect to the axis of pivot of the pivotable arms. This characteristic is beneficial in several respects. Foremost is that it enables a hinge geometry where the force application point from the force transfer element can be extremely close to the fulcrum of the hinges. This enables the ability to maximize the force transfer efficiency. An additional advantageous result of this geometry is that it enables a compact overall design of the apparatus. A further benefit is that the geometry is readily supportive of size scaling from approximately less than 1 cubic inch to approximately 20 cubic inches. This scalability in size provides the design envelope for a broad range of displacements from approximately 1/10,000 inch to approximately 0.25 inches. Similarly, the geometry provides for a wide range of clamping forces from less than 1 pound to more than 100 pounds. Yet another benefit is that the entire surface of both faces of the piezoelectric element remain in compressed contact with the opposing

faces of the support structure; namely, the rigid web 30 at one end and the force transfer element 26 at the opposite end.

[0040] In the embodiments illustrated in Figures 1-6, these components have been machined from a single piece of metallic material for example stainless steel. Other suitable materials can include powdered metal, metallic alloys, composite materials, or a combination of metallic and composite materials. Although these materials given as examples provide excellent performance, depending on the requirements of a particular application, use of other materials for the support can be appropriate.

[0041] While the invention has been described in connection with what is presently considered to be the most practical and preferred embodiment, it is to be understood that the invention is not to be limited to the disclosed embodiments but, on the contrary, is intended to cover various modifications and equivalent arrangements included within the spirit and scope of the appended claims, which scope is to be accorded the broadest interpretation so as to encompass all such modifications and equivalent structures as is permitted under the law.